Intense FEL light pulses with a length of three optical cycles produced at zero detuning of an optical cavity length

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Abstract

We have observed sustained saturation in a Free-Electron Laser (FEL) oscillator at zero detuning of an optical cavity length for the first time, and confirmed that the optical pulse length at zero detuning is 250 fs FWHM at wavelength of 22 μm. The optical length corresponds to three optical cycles, which is the fewest cycles ever achieved at FELs in the world. The peak FEL power reaches 0.8 GW with the single optical pulse energy of 200 μJ. The sustained lasing at zero detuning is not allowed in conventional FEL oscillator theories and the physical mechanism is under investigation.

1 INTRODUCTION

In a Free-Electron Laser (FEL) oscillator, spontaneous undulator radiation produced by an electron bunch is stored in an optical cavity and amplified through interactions with successive fresh electron bunches in the undulator. The FEL laser oscillations are, therefore, realized when the cavity length is tuned in a finite range near the length matched with the electron bunch interval. The lasing range is restricted to cavity lengths shorter than the zero detuning, where the cavity length is completely matched with the electron bunch interval, in the following reason. The trailing edge of the FEL light is mainly amplified during an interaction with a fresh electron bunch due to the slippage ($N_w\lambda$), which is a delay distance of the electron bunch to the FEL light in the undulator. The group velocity of the FEL light, therefore, becomes somewhat smaller than the vacuum speed of light. This is known as "laser lethargy" and optical cavity shortening is required to compensate the lethargy delay [1]. Here N_w is the number of undulator periods and λ is radiation wavelength.

The laser performances of FEL oscillators strongly depend on the length detuning (δL) of the optical cavity from the zero detuning (δL = 0). The FEL gain becomes maximum at the detuning length where the lethargy delay is most effectively compensated. The efficiency from electron beam power to FEL radiation becomes maximum near δL = 0, where the gain is small though, because the FEL light can interact with fresh electron bunches many round-trips before the FEL light is pushed out by δL with the round-trips. The FEL optical pulse length becomes shorter near δL = 0, because the trailing edge of the pulse grows mainly [2, 3].

At the zero detuning of FEL oscillators, the optical pulse centroid is retarded on successive passes and the optical pulses finally dissipate. Only a transient state therefore exists at δL = 0. This transient evolution of the optical pulses at δL = 0 is supported by numerical and analytical studies [1, 2].

We describe improvements of the JAERI-FEL system which contributed to "over 2 kW" lasing, in the next section. A numerical analysis on JAERI-FEL, which reproduces the high-power lasing observed in the JAERI-FEL oscillator, has clearly shown that the maximum efficiency is obtained at δL = 0 despite the lethargy in conventional FEL oscillator theories. This is discussed in section 3. The experimental confirmation of the sustained lasing at δL = 0 is presented in the section 4. The measured FEL pulse length at δL = 0 is only 3.4 cycles FWHM, which is the fewest cycles ever achieved at existing FELs. This is also presented in the section 4. A conclusion is given in the last section.

2 HIGH-POWER FEL OSCILLATION [4]

The project of JAERI-FEL, high average power FEL driven by a superconducting linac with frequency of 499.8 MHz, started in 1987 to provide a quasi-CW far infrared (FIR) laser of a 1 ms long macropulse at 10 Hz repetition rate. The early years of the project were devoted to the design study and construction of the linac system. The first lasing was obtained in Feb. 1998 [5] after improvements of the electron gun and RF feed-back circuits. The FEL power was gradually increased by achieving higher longitudinal brightness of driver electron bunches and optimizing output coupling scheme of FEL from an optical cavity, and eventually exceeded 2 kW in Feb. 2000 [4].

2.1 *Improvements of injection system [4, 6]*

Two modifications mainly contributed to generation of high brightness electron multi-bunches with a long macropulse duration. One is an improvement of an electron gun, the other is an optimization of a drift length between a 6th subharmonic buncher (SHB) and a first cell of the superconducting accelerator.

The electron gun at JAERI-FEL is a DC gun with a thermionic cathode driven by a grid pulser, and its DC voltage is 230 kV. The high voltage is very useful not only to reduce space charge effects, but also to keep a high speed of β = 0.71 in the low energy region. The accelerator tube and the grid pulser are contained in a tank filled with SF_6 insulation gas to avoid a discharge. An input signal into the grid pulser on the high voltage terminal is fed through an optical fiber, and has to go across an extra connector attached

Table 1: JAERI-FEL parameters.

Parameter	Measured
Kinetic energy	16.5 MeV
Average current	5.3 mA
Bunch charge	0.51 nC
Bunch length (FWHM)	< 5 ps
Peak current	> 100 A
Energy spread (rms)	1.2 %
Normalized emittance (rms)	40 mm mr (x)
	22 mm mr (y)
Bunch repetition	10.4125 MHz
Undulator period	3.3 cm
Number of undulator periods	52
Undulator parameter (rms)	0.7
Optical cavity length	14.4 m
Rayleigh range	1.00 m
Mirror radii	6 cm
Output wavelength	22 - 17 μm

to the tank. As the input signal is attenuated too much at the connector, the grid pulser is affected by a slight error source such as a stray capacitance. This causes the jitter of bunch intervals from the gun.

The time jitter at the gun causes arrival time fluctuations of electron bunches at an undulator. The fluctuation corresponds to the shift of the effective optical cavity length. The fluctuation should be reduced for high efficiency operation, because the efficiency is very sensitive to a slight shift of cavity length near δL = 0 μm [3]. Our numerical simulation indicates that the jitter inside the undulator should be smaller than 100 fs rms for the simulation to reproduce the shape of the detuning curve presented in Fig. 1 [7]. Realization of such very low time jitter at the undulator is mainly due to jitter reduction at the gun (see Ref. [6] for more details).

The drift length after the SHB must be adjusted so that the bunch is compressed effectively, and it was shortened from 7.4 m to 4.5 m in 1999 [6]. The FEL power was gradually increased by adjusting accelerator phases, optimizing output coupling methods [8], reducing the time jitter of the gun, and removing frequency fluctuation of a master oscillator. The FEL power finally became 10 times higher than it obtained in 1999, and the peak current of electron bunches was obtained to be 100 A from the bunch length, 5 ps FWHM, measured with a synchroscan streak camera (M1954-10, Hamamatsu) at the undulator center. The above bunch length is almost comparable to trigger jitter of the streak camera and the bunch may have the shorter length and the higher peak current. The parameters for the electron bunch and the FEL are listed in Table 1.

2.2 *Optimum output coupling of FEL light [8]*

The wavelength in JAERI-FEL ranges from 22 to 17 μm where dielectric mirrors are not available as output couplers. A center hole on an optical cavity mirror or a scraper

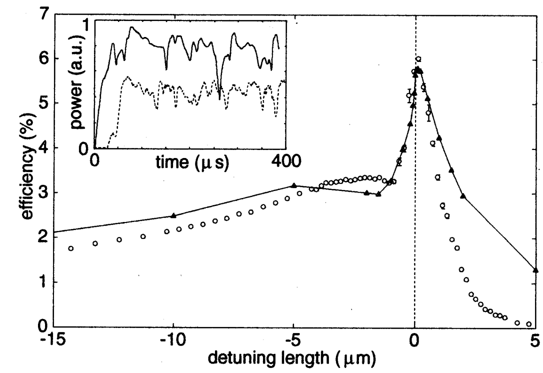

Figure 1: The open-circles are typical measured efficiencies as a function of δL in JAERI-FEL. The solid-triangles are our numerical results, which agree with the measured efficiency curve well. The solid-line is a guide to the eye. The above left shows typical optical macropulses at δL = 0 from our simulation (solid-line) and an experiment (dashed-line). It should be noted that the transversal axis for experimental data is relative detuning length, while it for the numerical data is absolute one.

mirror are used as output couplers in JAERI-FEL. The output coupler using the hole or the scraper mirror offers broadband operation, but diffraction loss due to scattering from the coupler edge becomes comparable to or larger than the coupled FEL power. The ratio between the diffraction loss and output FEL power decreases with increasing radius of the hole or the scraper mirror, while the total loss also increases and the FEL efficiency decreases. There is an optimum coupling scheme for maximum FEL output.

The scraper can couple out the outer part of the transversal profile of the FEL light, while the center hole couples out the most intense part of the FEL for the lowest transversal eigen-mode of the optical cavity. This means that radius of the scraper mirror is larger than the hole for the same FEL output power, and the scraper mirror is more efficient. An iterative calculation based on Fox-Li procedure [9] has been made to obtain an optimum coupling scheme (see Ref. [8] for more detail).

3 NUMERICAL STUDY ON JAERI HIGH-POWER FEL [7]

An interesting feature of the efficiency detuning curve in JAERI-FEL is the sharp peak observed at the maximum efficiency (see Fig. 1). Here the detuning length of the measured efficiency curve (open circles) is relative value, and the detuning length at the maximum efficiency is tentatively defined as δL = 0 μm. The efficiency gradually increases from $\delta L = -30$ μm to -1 μm, but is steeply enhanced from -1 μm to 0 μm. The enhancement of the efficiency is about 80 %. The sharp peak has not been observed in other FELs [10]. A numerical analysis is made to characterize the lasing behavior by using a 1-D time-

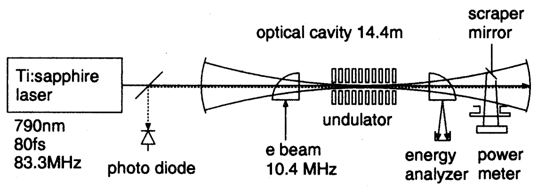

Figure 2: An experimental setup for a simultaneous measurement of FEL power and absolute cavity length.

dependent code based on a macro-particle model [11]. A shot-noise of the bunch is also introduced into the simulation according to Penman's method [12], which gives the effective shot-noise derived from statistical consideration. An efficiency curve simulated with the dimensionless beam current [13], $j_0 = 50$, is shown as solid-triangles in Fig. 1 and agrees with the experimental data well.

The important indication of the numerical simulation is that the efficiency is maximum at $\delta L = 0\ \mu$m and the lasing is sustained despite the laser lethargy. However, no measurement has been made at FEL oscillators with enough accuracy to claim the lasing at $\delta L = 0$ [10, 3]. For an experimental confirmation of the lasing at $\delta L = 0$, we made a simultaneous measurement of FEL power and absolute detuning length, as described in the next section.

It was also found that our numerical simulation without the shot-noise gives a result consistent with the studies by Colson [1] and Piovella [2], in which no stationary lasing exists at $\delta L = 0$ with non-zero optical cavity loss. Thus the small shot-noise largely affects the lasing dynamics at the zero detuning, although the coherent component of the shot-noise has small power, 10^{-10} of the saturated FEL power in our simulations, and does not affect the efficiency curve directly. Typical optical macropulses at $\delta L = 0\ \mu$m from the simulation (solid-line) and an experiment (dashed-line) are shown in the above left in Fig. 1 with an arbitrary unit in the vertical axis. They are similar with each other.

The temporal profile at $\delta L = 0\ \mu$m obtained by the simulation is a short, single optical spike with length of 300 fs FWHM without subpulses even after saturation. We measured the temporal profile to confirm the numerical indication, as described in the next section. Details of our simulation will appear in elsewhere [7].

4 SHORT, INTENSE FEL AT $\delta L = 0$

4.1 Sustained lasing at $\delta L = 0$ [14]

The experimental setup for verification of lasing at $\delta L = 0$ is shown in Fig. 2. The absolute detuning length was measured with a mode-locked Ti:sapphire laser (Tsunami 3960, Spectra-Physics) synchronized with the frequency of 83.30000 MHz, which is the eighth harmonic of the electron bunch repetition rate and supplied from the same RF source used for the accelerator system [15]. The pulse length of the laser is about 80 fs FWHM. The laser pulses

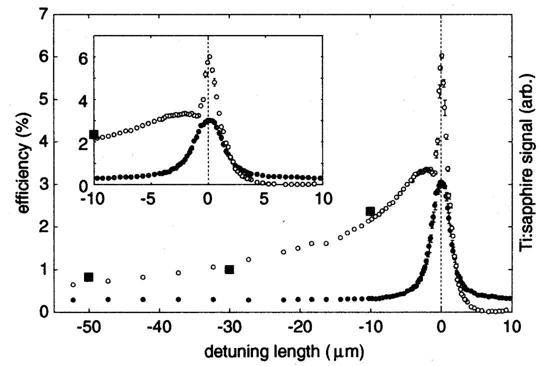

Figure 3: FEL efficiencies (open-circles) and Ti:sapphire signals (solid-circles) as a function of detuning length. The enlargement around $\delta L = 0\ \mu$m is also shown. The symbols without error-bars have error less than their size. The absolute vertical scale was calibrated by average energy loss of the electron beam over an entire macropulse (solid-squares) at several detuning lengths.

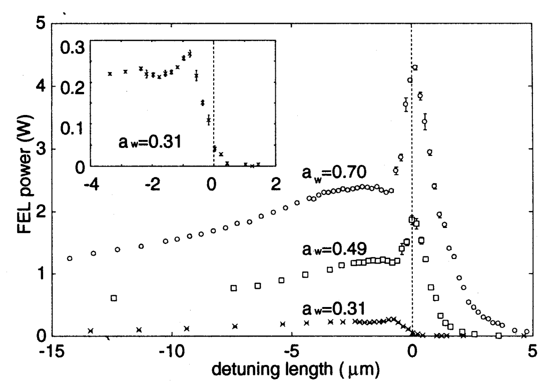

Figure 4: FEL power measured as a function of detuning length with different undulator parameters: 0.70 (open-circles), 0.49 (open-squares), and 0.31 (crosses). The macropulse duration is 0.4 ms at 10 Hz repetition rate. The enlargement around $\delta L = 0\ \mu$m for $a_w = 0.31$ is also shown.

were injected into the optical cavity through a glass window, which does not transmit FIR light, and a center hole with 2 mm in diameter on an upstream cavity mirror. The stored pulses were coupled out through the same hole and detected by an avalanche photo detector (C1536-01, Hamamatsu). The detector signal is enhanced by the pulse stacking, if an optical cavity is tuned at an appropriate length [16]. Mean values of the photo detector signal over 200 ms duration were measured by a digital oscilloscope (TDS 684B, Tektronix) at a peak detection mode. The measurement was repeated five times at each detuning length. The experimental results exhibit a clear resonance peak as shown in Fig. 3, where each error-bar is the standard deviation of the five repeated measurements. The centroid of the resonance peak was determined with the accuracy of 0.01

μm, by fitting the data with Gaussian distribution.

The FEL light was coupled out by a gold-coated scraper mirror of 18 mm in diameter, which was installed at 0.5 m away from the downstream mirror and 23 mm from the center axis of the optical cavity, and was extracted through a KRS5 window. The FEL power was measured with a power-meter placed near the window and acquired by the oscilloscope in the same manner as the Ti:sapphire signal. The typical maximum power was 4.4 W at macropulse duration of 0.4 ms with 10 Hz repetition rate. This measured power is equal to 1.1 kW at a macropulse average. The experimental data are plotted as open-circles in Fig. 3. For the calibration from the FEL power to the efficiency, we measured average energy loss of the electron beam over an entire macropulse at several detuning lengths. The loss measurement was made with the energy analyzer placed after the undulator, which has the energy acceptance of 20 %, and the measurement was restricted to the larger detuning length beyond $\delta L = -10$ μm where the total energy spread was 17 %. The FEL power and Ti:sapphire signal were simultaneously measured at equal steps of 0.2 μm around the maximum FEL power within two minutes. This quick measurement is necessary to reduce the uncertainty caused by slowly evolving drifts of the cavity length due to thermal strain and other sources. A separate measurement confirms that the maximum FEL power is held with variation of 2.3 % rms and the amplitude change of the Ti:sapphire signal is 2.0 % rms over two minutes.

As shown in Fig. 3, the peak of the FEL efficiency curve coincides with the resonance peak of the Ti:sapphire signal within the accuracy of 0.1 μm. This is the first demonstration of sustained saturation at the zero detuning. As the maximum efficiency is 6 % with the electron beam power of 88 kW, the extracted FEL power should be 5 kW at a macropulse average. The total loss of the optical cavity with and without the scraper mirror was measured to be 7.6 $\pm$ 0.3 % and 3.3 $\pm$ 0.2 %, respectively, from a cavity ring down of FEL with a Ge-Cu detector. The FEL coupling rate from the cavity is therefore estimated to be about 30 % on the assumption of coupling rate of 50 % at the scraper mirror itself [17]. The transmittance of a KRS5 window for λ = 22 μm light is about 70 % in normal incidence. Consequently, the estimated output FEL power from the measured efficiency is consistent with the experimental value of 1.1 kW with the power meter.

It should be noticed that the numerical study by Colson, which shows only a transient FEL evolution at δL = 0, also includes a shot-noise effect and uses the coupling mode parameter μ_c = 1 similar to the present study [1]. The parameter μ_c is defined as $\mu_c = N\lambda/2\sigma_e$, where N is the number of undulator periods and σ_e is the rms electron bunch length [18]. The main difference is the dimensionless beam current, j_0 = 50, in JAERI-FEL, while j_0 = 5 is used in the simulation by Colson. In order to study the lasing dynamics at smaller j_0, we measured efficiency curves at three different rms undulator parameters of a_w = 0.70, 0.49, and 0.31 by widening the undulator gap. The currents j_0 are estimated to be 50, 22, and 10, respectively, on the definition of $j_0 \propto (a_w[JJ])^2/(1 + a_w^2)$ [13]. Here, $[JJ]$ is the Bessel function for a planar undulator. The detuning length of each efficiency curve was calibrated by the Ti:sapphire laser, independently. The experimental results shown in Fig. 4 exhibits that the lasing dynamics at δL = 0 depends on the dimensionless beam current, and the sustained saturation at δL = 0 disappears at j_0 = 10. This result is consistent with the Colson's simulation at j_0 = 5.

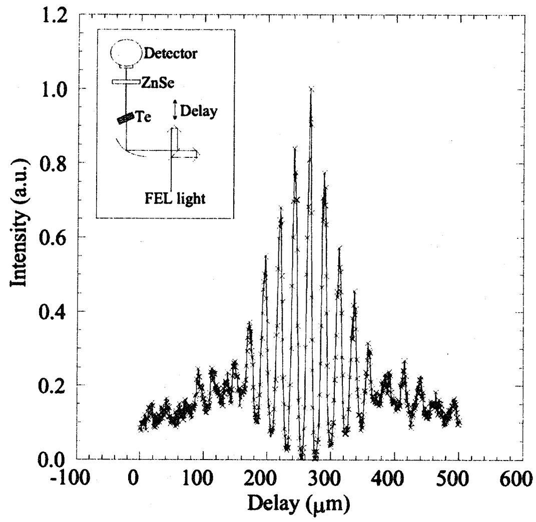

Figure 5: Second-order autocorrelation measurement for a wavelength of 22 μm at zero detuning of an optical cavity. The pulse length is 250 fs FWHM with assumption of $\mathrm{sech}^2(t)$ pulse. This corresponds to 3.4 field cycles. The above left shows second-order autocorrelation setup, based on second harmonic generation in a Te crystal.

4.2 *Intense FEL with three optical cycles [19]*

Short, intense optical pulses in the FIR spectral range are useful for studies on dynamic properties of a wide variety of semiconductor systems. An FEL oscillator is appropriate for producing such short, intense FIR lights. The FEL pulse length strongly depends on δL, because the FEL pulse is pushed forward due to δL and evolves into a train of subpulses. A short-pulse FEL with a length of six optical cycles has been already demonstrated in FELIX at wavelengths of 10.4 and 24.5 μm at $\delta L = -1$ and -3 μm, respectively [20]. The reason why the temporal profiles in FELIX are subpulse-free smooth single pulses is that the measurements in FELIX were made in start-up phase of the FEL evolution due to the restricted macropulse duration.

The macropulse duration in JAERI-FEL is enough long to reach saturation near δL = 0, and the experimental confirmation of the lasing at δL = 0 stimulated us toward study of the temporal FEL profile at δL = 0: whether a short, subpulse-free single pulse is obtained at δL even after saturation, as shown in our simulation [7]. We measured the pulse length of the JAERI-FEL FIR light using second-order autocorrelation, in a time range after the FEL saturation. The experimental setup is shown in the above left of Fig. 5. The second-harmonic generation in a 2-mm-long Te crystal was used to provide the nonlinear autocorrelation signal. The Te crystal is birefringent and phase-matching can be realized easily by setting orientation of the crystal to an appropriate angle. Residual fundamental FEL through the Te crystal were blocked by a ZnSe filtter. Higher-harmonic signals of the FEL light are negligible, because the second-harmonic conversion efficiency of the Te crystal is sufficiently high [21].

The observed autocorrelation signal is shown in Fig. 5. The pulse length is 250 fs FWHM, which corresponds to only 3.4 optical cycles, with assumption of $\mathrm{sech}^2(t)$-pulse shape. This agrees with the numerical result well [7], and shows that a smooth single pulse is quasi-continuously generated during a macropulse duration. The maximum pulse energy is 200 μJ [4], and the peak FEL power reaches 0.8 GW.

5 CONCLUSION

We have observed sustained saturation in FEL oscillators at zero detuning of an optical cavity for the first time, although it has been considered that a transient solution only exists at the zero detuning due to the laser lethargy, so far. The FEL efficiency becomes maximum at $\delta L = 0$, if the dimensionless beam current is large enough. A train of short, intense FEL pulses with only three optical cycles has been quasi-continuously generated at $\delta L = 0$.

The efficiency detuning curve and the short-pulse at $\delta L = 0$ are well reproduced by our numerical simulation including a shot-noise effect. The physical mechanism of the lasing at $\delta L = 0$ is under progress (see Ref. [22] for more informations and "http://hobbit.tokai.jaeri.go.jp/papers" about JAERI-FEL activity).

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